

Jet properties from the conditional yields associated with high- p_T π^0 and direct photon

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for the PHENIX collaboration



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Why to study direct photon correlation

Inclusive distributions - R_{AA} - limited sensitivity to details of parton interaction with QGP

- Energy loss probability distribution and surface bias
- π vs p R_{AA} quark vs gluon R_{AA} similarity
- π vs direct gamma R_{AA} similarity
- Light vs heavy quark R_{AA} (non-photonic electron) similarity

Two particle correlations - more detailed view into a nature of parton interactions with QCD medium. Access to parton intrinsic momentum k_T -> soft pQCD radiation, jet shape parameters j_T -> induced radiation, fragmentation function -> energy loss.

- Di-hadron correlations and conditional yields
- Direct photons-hadron correlations in $p + p$ @ $\sqrt{s}=200$ GeV

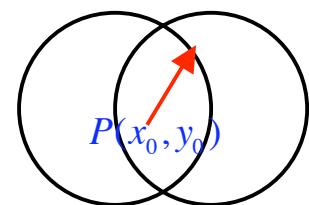
R_{AA} sensitivity to $P(\Delta E, E)$?

T. Renk, k. Eskola *et al.*

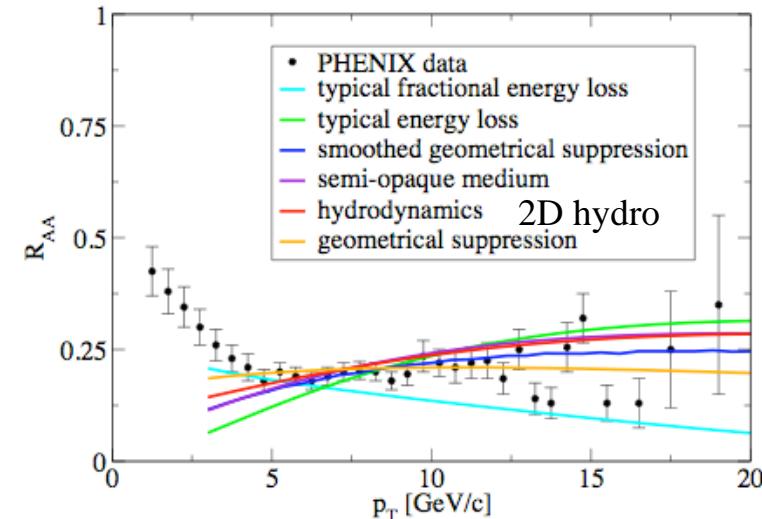
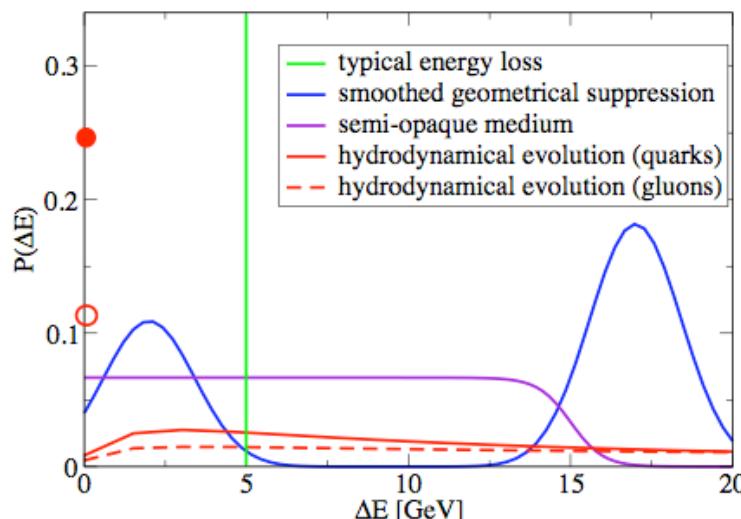
R_{AA} uniquely determined by $p_{had} = p_{part} \otimes \langle P(\Delta E, E) \rangle \otimes D_{f \rightarrow \pi}^{vac}(z, \mu_F^2)$

The E-loss probability can be defined:

$$\langle P(\Delta E, E) \rangle_{TAA} = \frac{1}{2\pi} \int_0^{2\pi} d\varphi \int_{-\infty}^{\infty} dx_0 \int_{-\infty}^{\infty} dy_0 P(x_0, y_0) P(\Delta E, E)_{path}$$



Where hard vertices $P(x_0, y_0) = \frac{[T_A(r_0)]^2}{T_{AA}(0)}$ and $T_A(\vec{r}) = \int dz \rho_A(\vec{r}, z)$



R_{AA} sensitivity - surface bias

Medium tomography:

T. Renk, K. Eskola

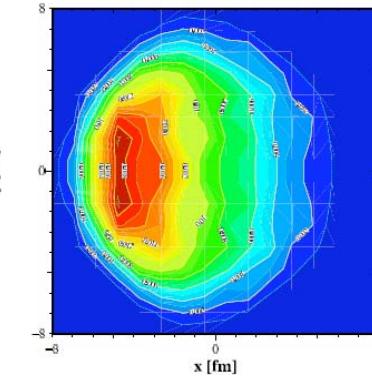
hep-ph/0610059

$$P(x_0, y_0) \Big|_{\text{single detected}}$$



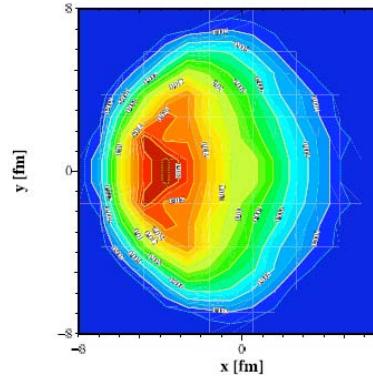
Singles: $8 < p_T < 15$

Hydrodynamics

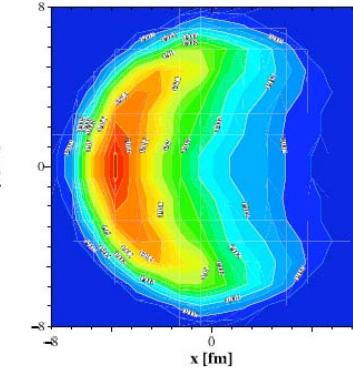


(near side $\equiv -x$)

Box density



Hydrodynamics - black core

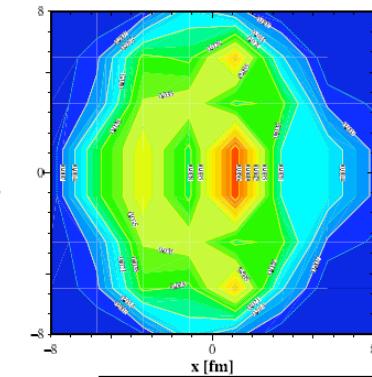


$$P(x_0, y_0) \Big|_{\text{dihadron detected}}$$

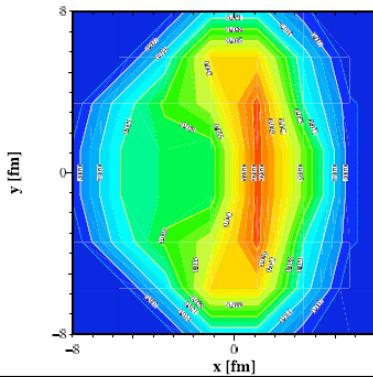


Dihadron: $(8 < p_T < 15) \otimes (4 < p_T < 6)$ GeV/c

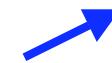
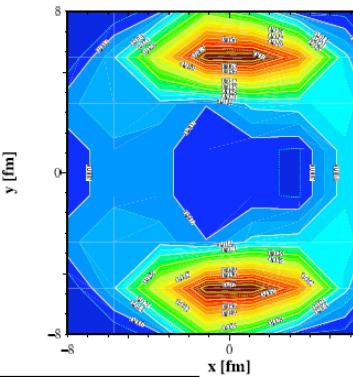
Hydrodynamics



Box density



Hydrodynamics black core

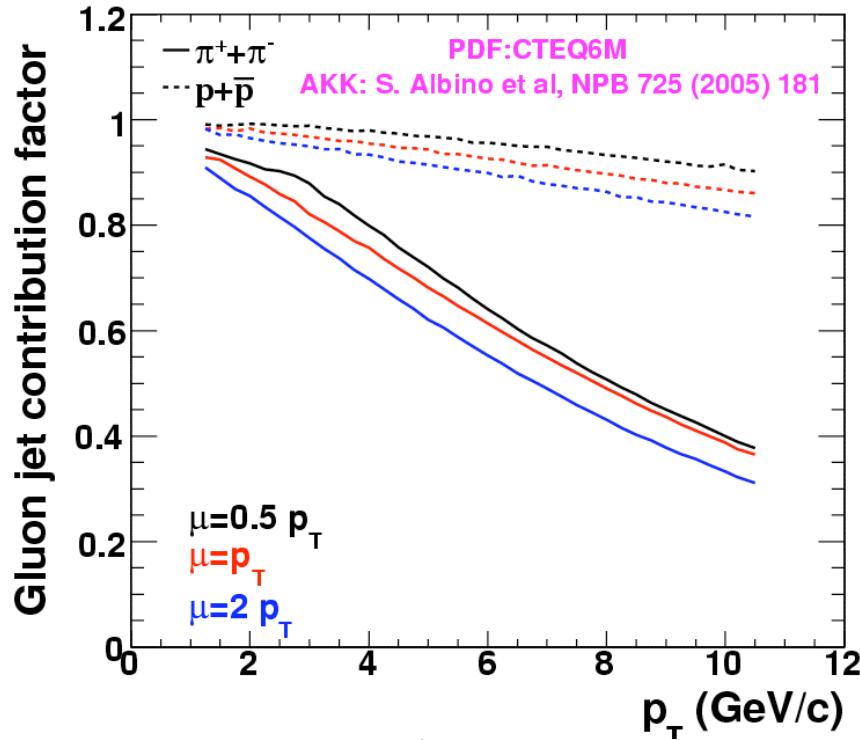


What do we learn from R_{AA} about the mechanism of *quark* and *gluon* interaction with QGP ? MJT comment:

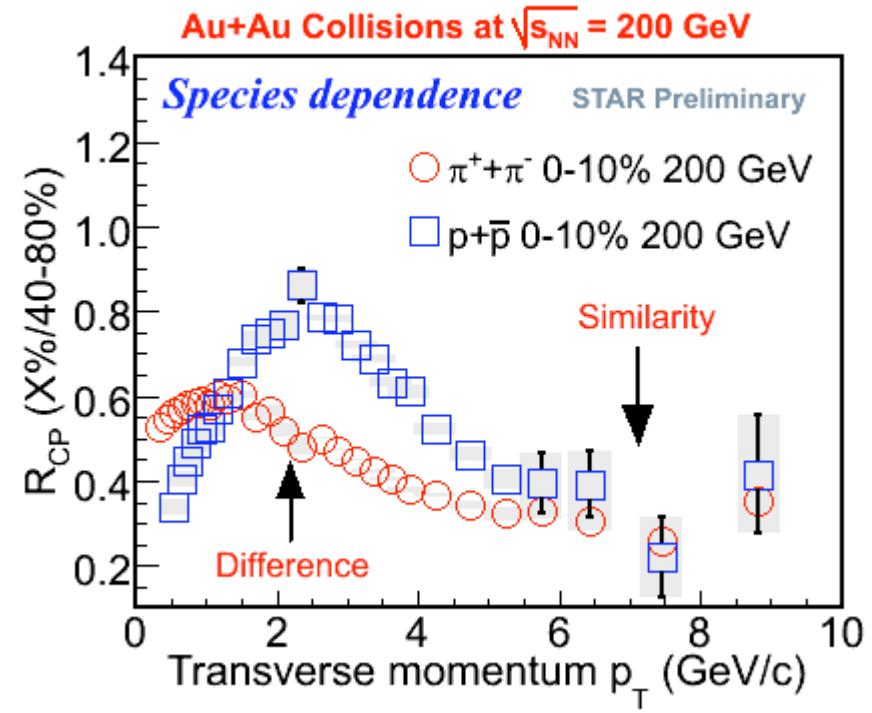
“Theory is interesting only if it doesn’t agree with the data.”

pions versus protons

$$R_{AA}^{\text{quark}} \approx R_{AA}^{\text{gluon}}$$



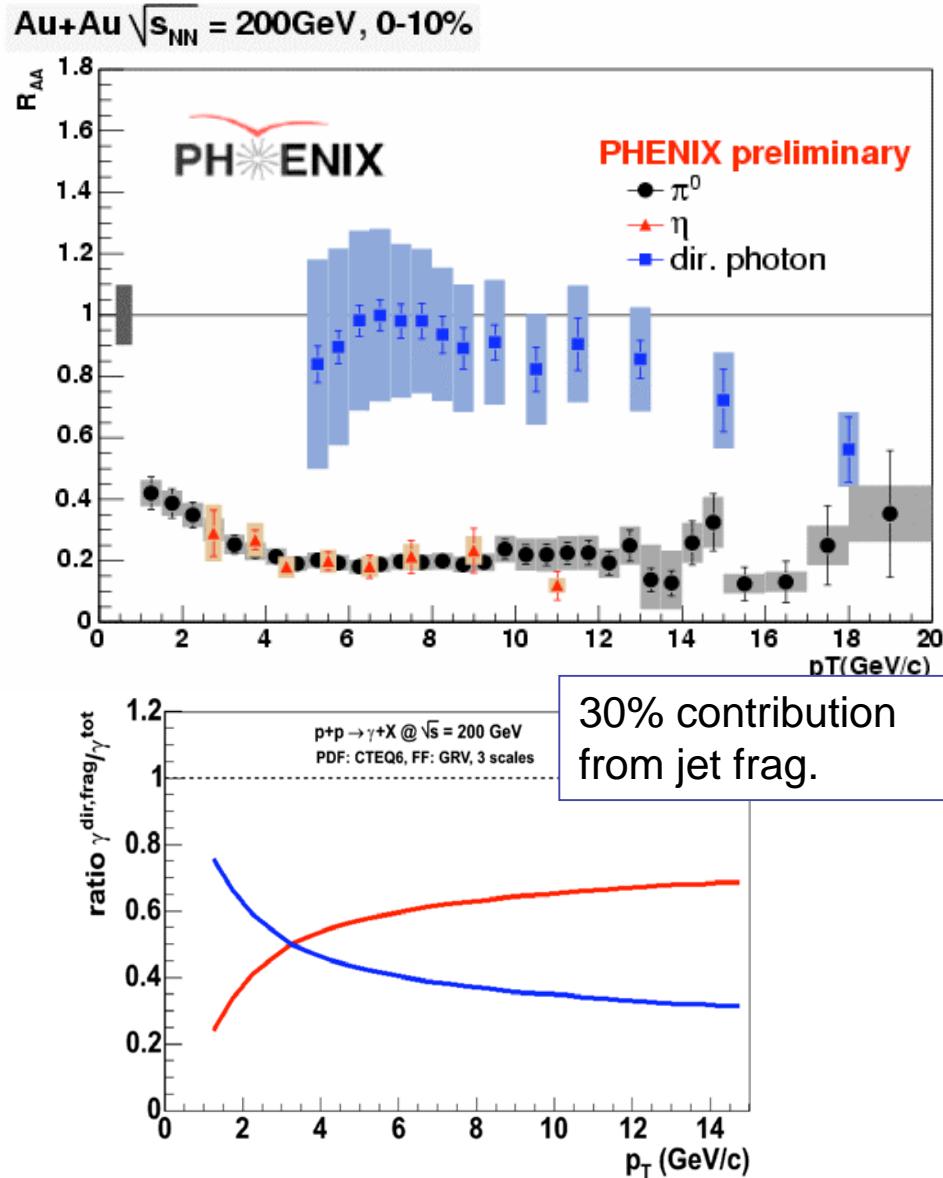
At high p_T , the p/π^+ ratios can be directly compared to results from quark jet fragmentation as measured in $e^+ + e^-$ collisions by DELPHI [29], indicated by the dotted-dashed line in Fig. 4(a). The p/π^+ ratio measurements in d+Au and Au+Au collisions are higher than in quark jet fragmentation. This is likely due to a significant contribution from gluon jets to the proton production, which have a $(p + \bar{p})/(\pi^+ + \pi^-)$ ratio up to two times larger than quark jets [30]. A similar comparison cannot



Question raised by STAR at QM06:
shouldn't be p and π supp. differently
due to C_A / C_F ?

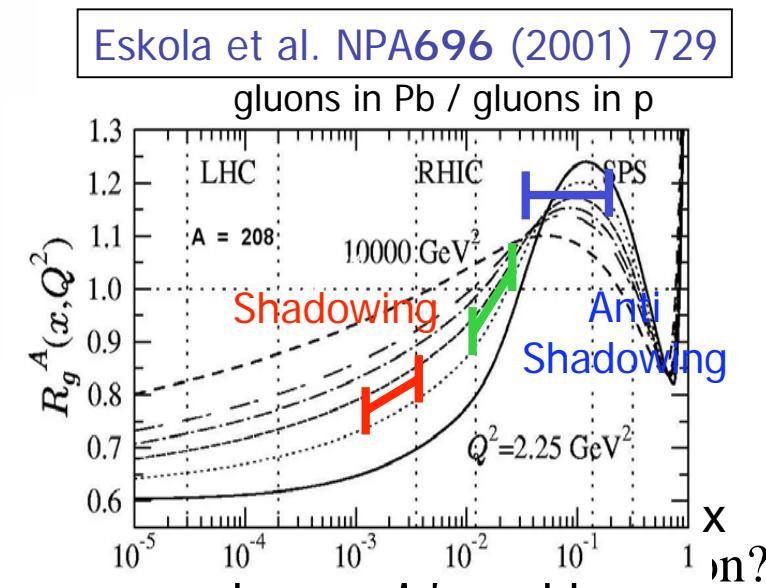
Question: high- p_T photons

$$R_{AA}^{q,g} \approx R_{AA}^{\gamma}$$



At high- p_T direct- γ almost as suppressed as π^0 .

Is it shadowing?



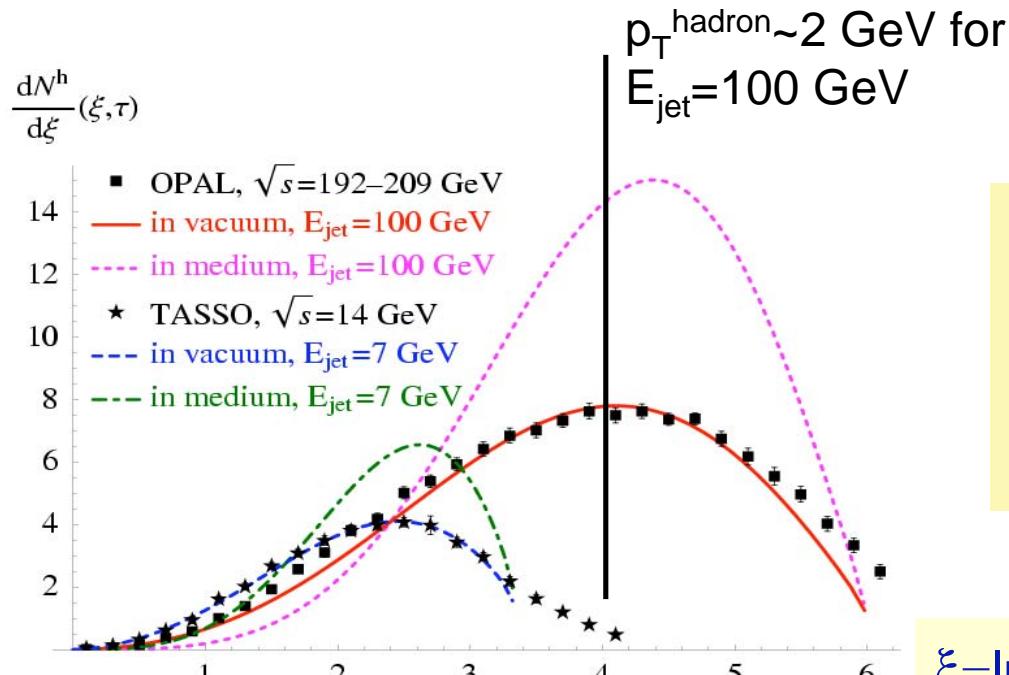
(Taadaki Isobe, QM06)

pQCD quenching - modification of $D(z)$

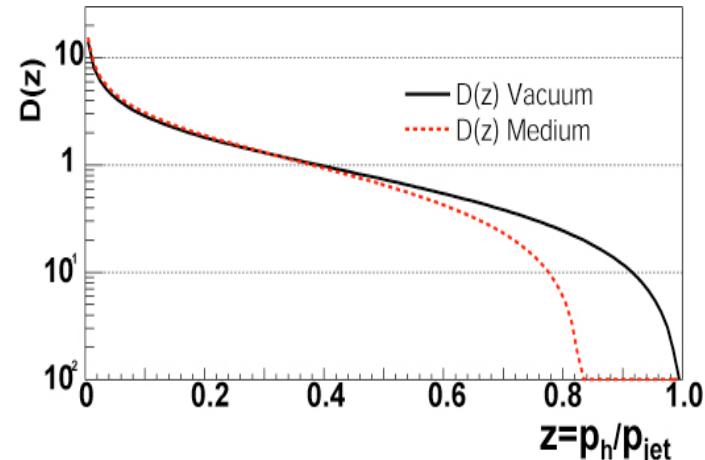
$$D(z) \equiv dN/dz, \quad z = p(\text{fragment})/p(\text{jet})$$

$$\tilde{D}(z) \approx \frac{1}{1-1/\Delta E} D\left(\frac{z}{1-\Delta E/E}\right)$$

Wang, X.N., Nucl. Phys. A, 702 (1) 2002



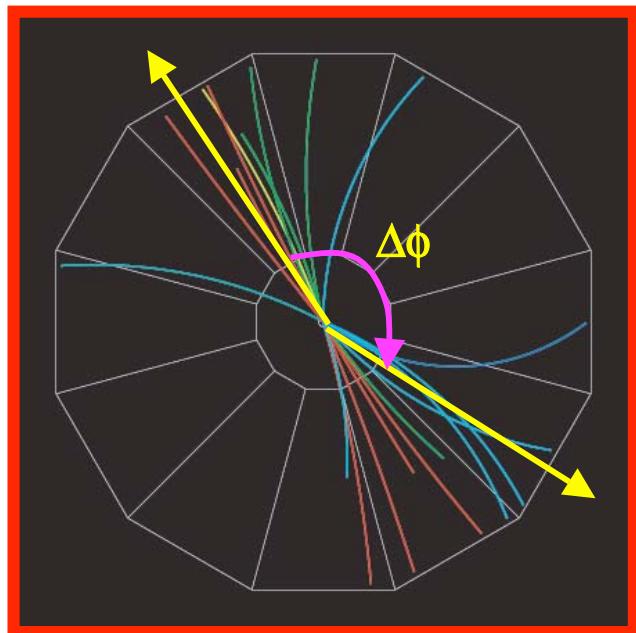
Borghini and Wiedemann, hep-ph/0506218



- MLLA: parton splitting+coherence \Rightarrow angle-ordered parton cascade. Theoretically controlled, experimentally verified approach
- Medium effects introduced at parton splitting

$$\xi = \ln(E_{\text{Jet}}/p_{\text{hadron}})$$

Azimuthal correlation function in $p+p$ @ $\sqrt{s}=200$ GeV

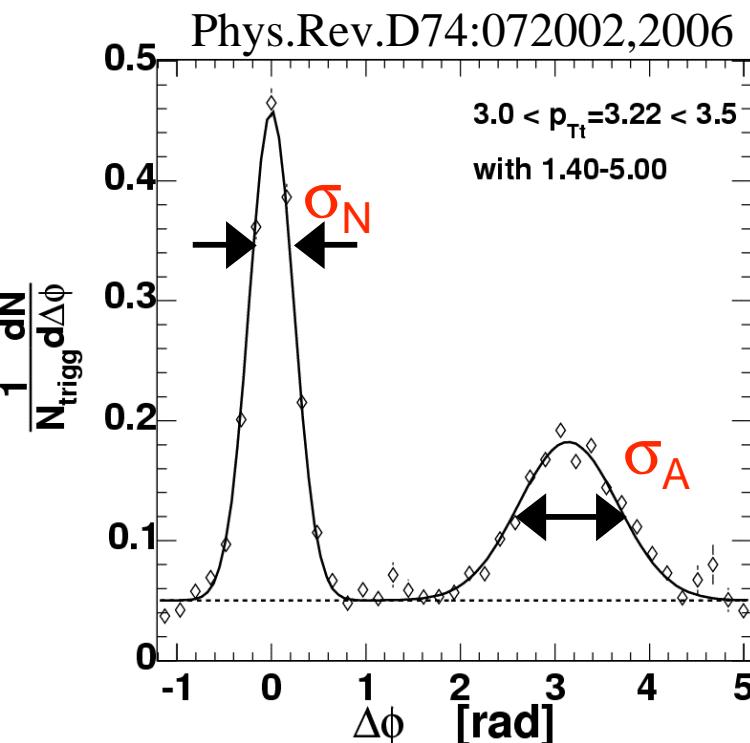


$p + p \rightarrow \text{jet} + \text{jet}$

$\sigma_N \propto \langle j_T \rangle$ jet fragmentation transverse momentum

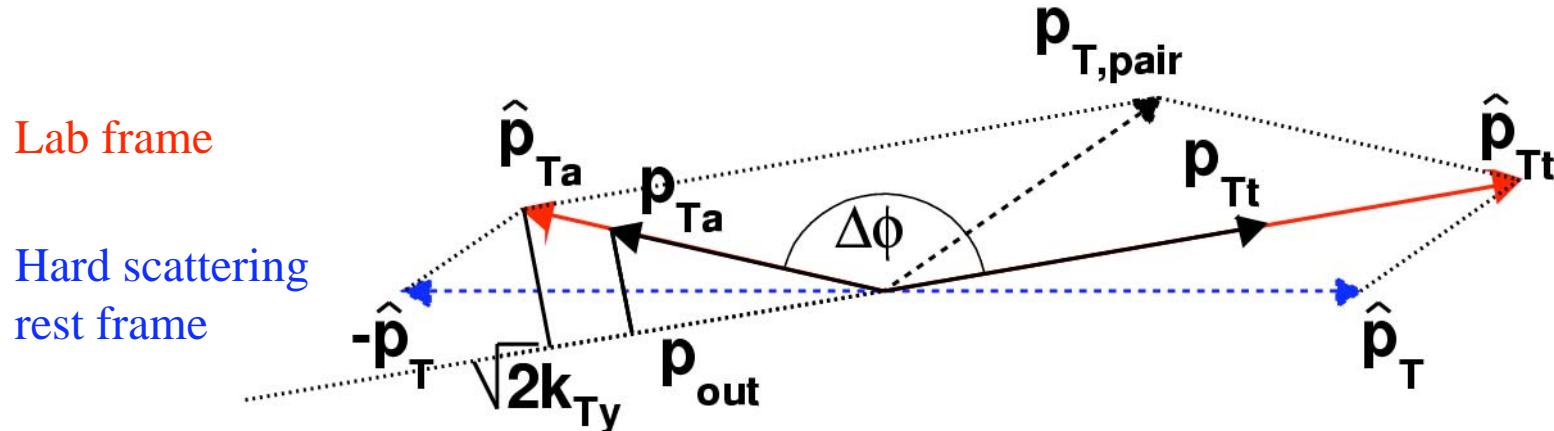
$\sigma_F \propto \langle k_T \rangle$ parton transverse momentum

$Y_A \propto$ folding of $D(z)$ and final state PDF.



k_T and acoplanarity

$p_{T,\text{pair}}$ Lorentz boost preserves $M_{\text{inv}}^2 = 4 \hat{p}_T^2 = 2 \hat{p}_{Tt} \hat{p}_{Ta} - 2 \vec{\hat{p}}_{Tt} \vec{\hat{p}}_{Ta}$



$$\langle |p_{out}| \rangle = \sqrt{2} \langle |k_{Ty}| \rangle \frac{p_{Ta}}{\langle \hat{p}_{Ta} \rangle} \quad \Rightarrow \quad \sqrt{\langle p_{out}^2 \rangle} = \langle z_t \rangle \sqrt{\langle k_T^2 \rangle} \frac{x_h}{\hat{x}_h}$$

Jet momenta imbalance
due to k_T smearing

$$\hat{x}_h = \frac{\langle \hat{p}_{Ta} \rangle}{\langle \hat{p}_{Tt} \rangle} \qquad \qquad x_h = \frac{p_{Ta}}{p_{Tt}}$$

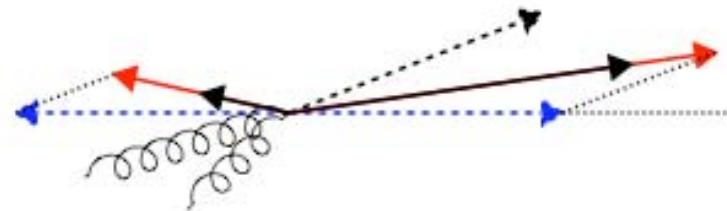
partonic $\hat{x}_h^{-1} \langle z_t \rangle \sqrt{\langle k_T^2 \rangle} = x_h^{-1} \sqrt{\langle p_{out}^2 \rangle - \langle j_{Ty}^2 \rangle (1 + x_h^2)}$ hadronic

"Averaged" pQCD approach

Assumptions (*Phys.Rev.D74:072002,2006 for details*) :

1. Invariant mass of mass-less partons in hard-scattering CMS and in LAB is the same -> non-Gaussian k_T -smearing

$$M_{inv}^2 = 4 \hat{p}_T^2 = 2 \hat{p}_{Tt} \hat{p}_{Ta} - 2 \vec{\hat{p}}_{Tt} \vec{\hat{p}}_{Ta}$$



2. Effective parton distribution function: $\Sigma_Q(\hat{p}_T) \propto \hat{p}_T^{-n}$
3. Effective Fragmentation function: $D(z) = z^\alpha \cdot (1-z)^\beta \cdot (1+z)^\gamma$

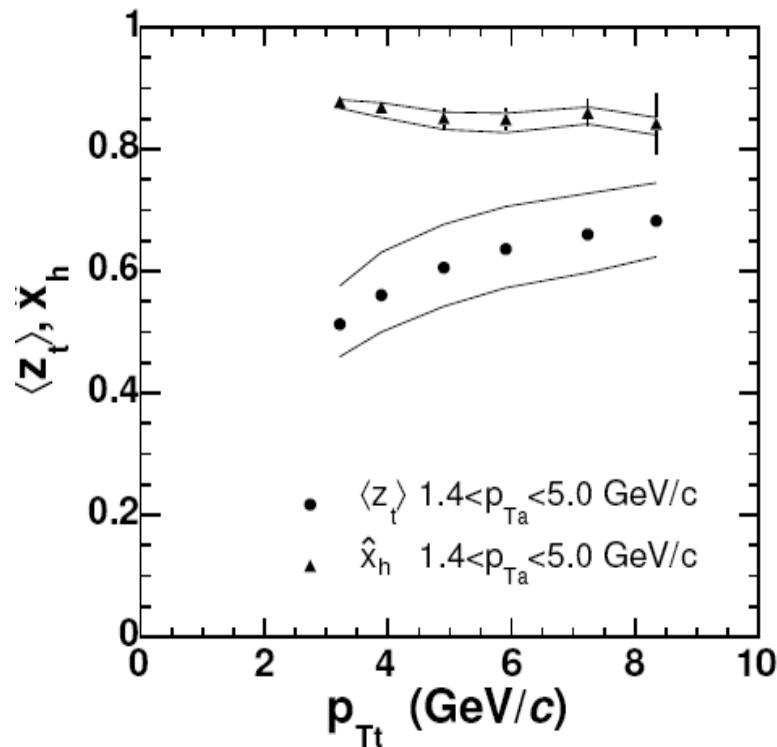
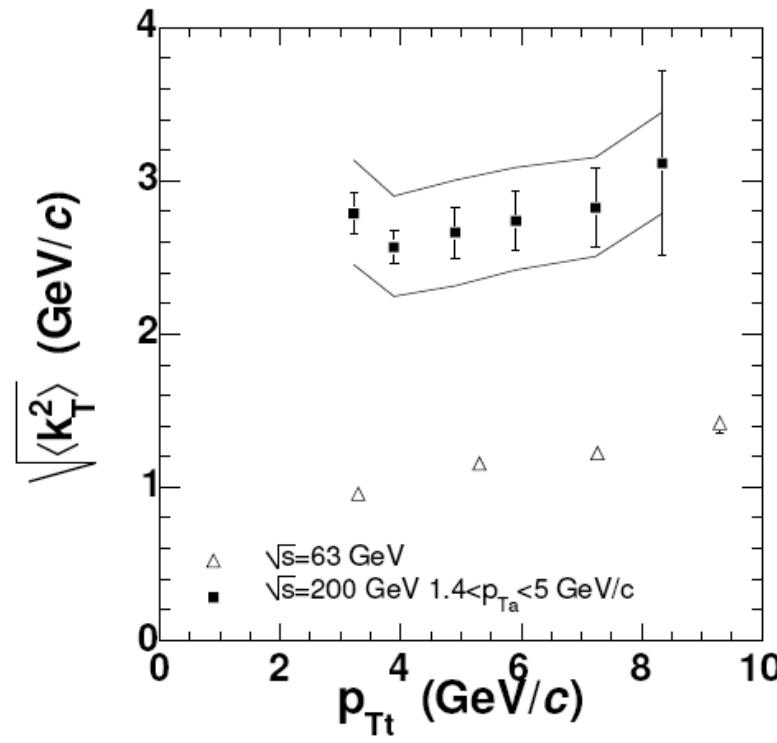
One can then evaluate:

1. Inclusive π^0 cross section
$$\frac{1}{p_T} \frac{d\sigma_\pi}{dp_T} = \int_{x_T}^1 \frac{dz}{z^2} \cdot D(z) \cdot \Sigma_Q\left(\frac{p_T}{z}\right)$$

2. Trigger π^0 associated dist.
$$\frac{d^2\sigma_\pi}{dp_{Tt} dp_{Ta}} = \frac{1}{p_{Tt}} \int_{x_{Tt}}^1 \frac{dz_t}{z_t} \cdot D(z_t) \cdot D\left(\frac{p_{Ta}}{p_{Tt}} z_t\right) \cdot \Sigma_Q\left(\frac{p_{Tt}}{z_t}\right)$$

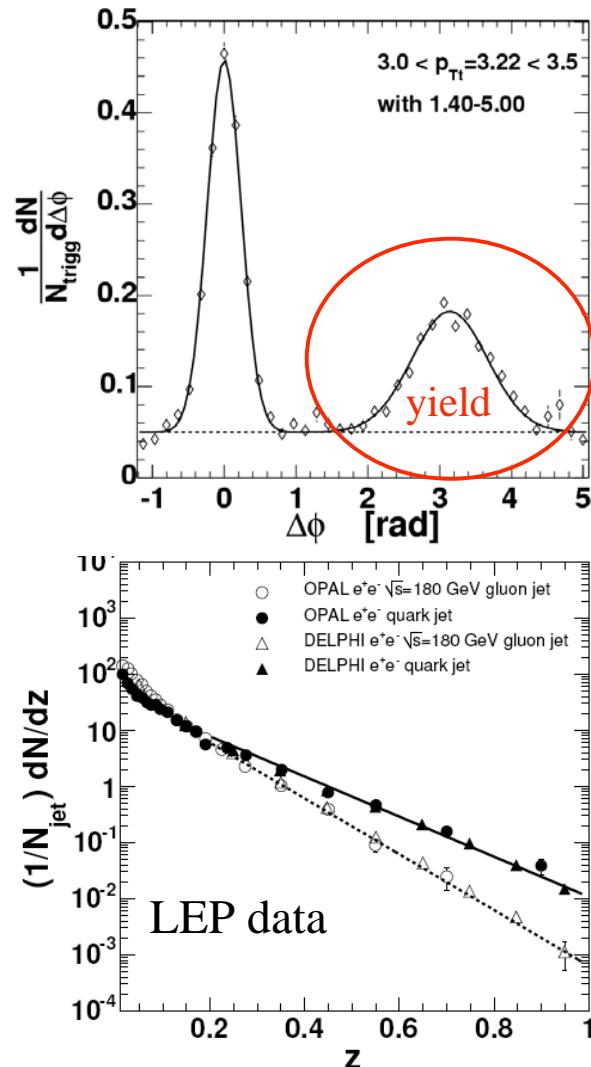
$\sqrt{\langle k_T^2 \rangle}$ and $\langle z_t \rangle$ in p+p @ 200 GeV

Phys.Rev.D74:072002,2006

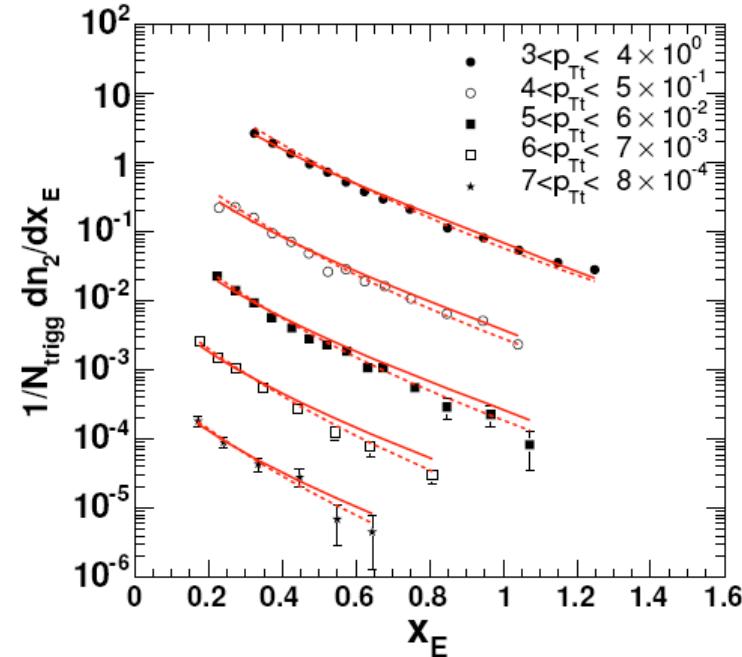


For D(z) the LEP date were used. Main contribution to the systematic errors comes from unknown ratio gluon/quark jet => D(z) slope.

Trigger associated spectra are insensitive to $D(z)$



$$x_E = \left| \frac{\vec{p}_{Ta} \cdot \vec{p}_{Tt}}{\vec{p}_{Tt}^2} \right| = -\frac{p_{Ta}}{p_{Tt}} \cos \Delta\phi \approx -\frac{p_{Ta}}{p_{Tt}}$$



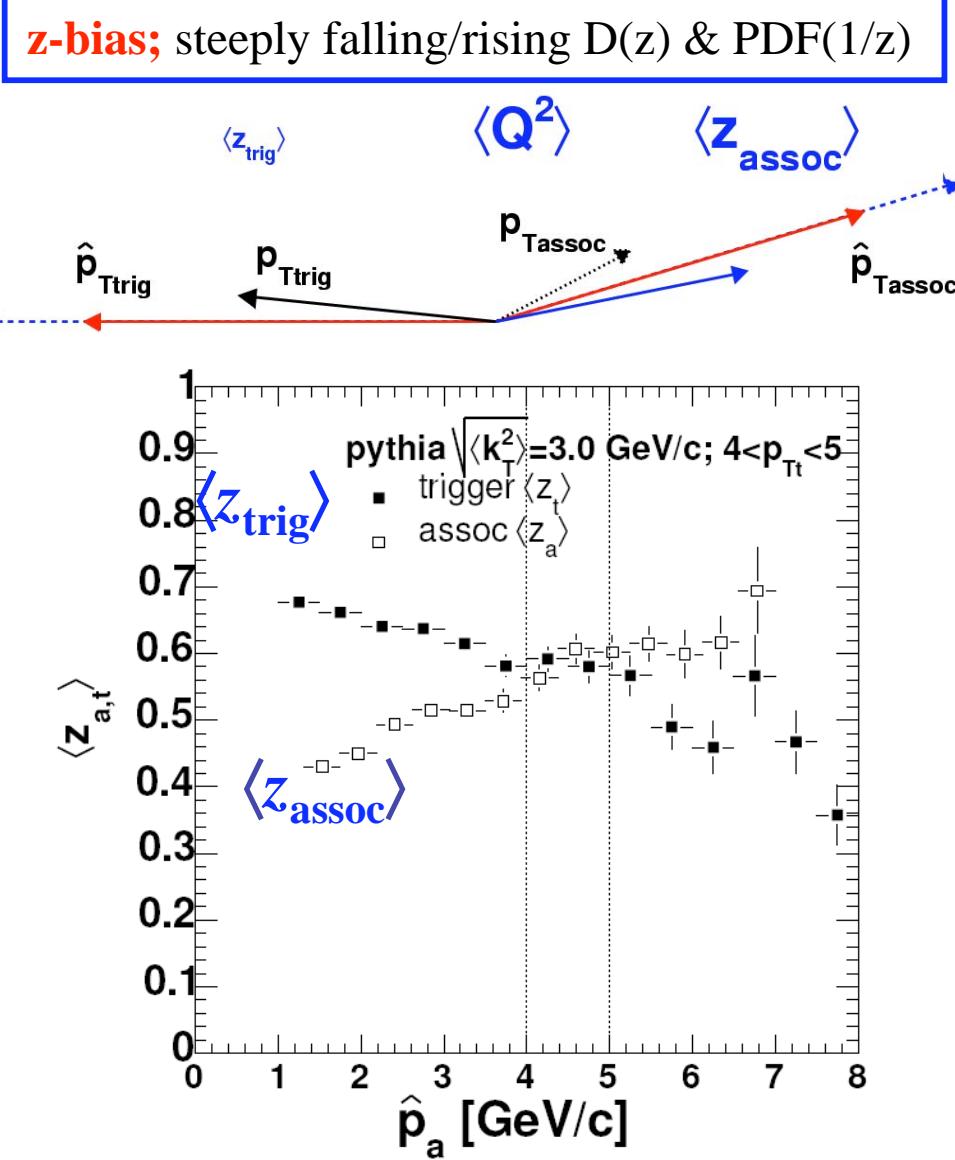
MJT Approximation - Incomplete Gamma function when assumed power law for final state PDF and exp for $D(z)$

$$\frac{d\sigma_\pi}{dp_{Tt}} = \frac{1}{p_{Tt}^{n-1}} \int_{xTt}^1 dz_t z_t^{n-2} e^{-b.z_t} \approx \langle m \rangle (n-1) \frac{1}{\hat{x}_h} \left(1 + \frac{x_E}{\hat{x}_h} \right)^{-n}$$

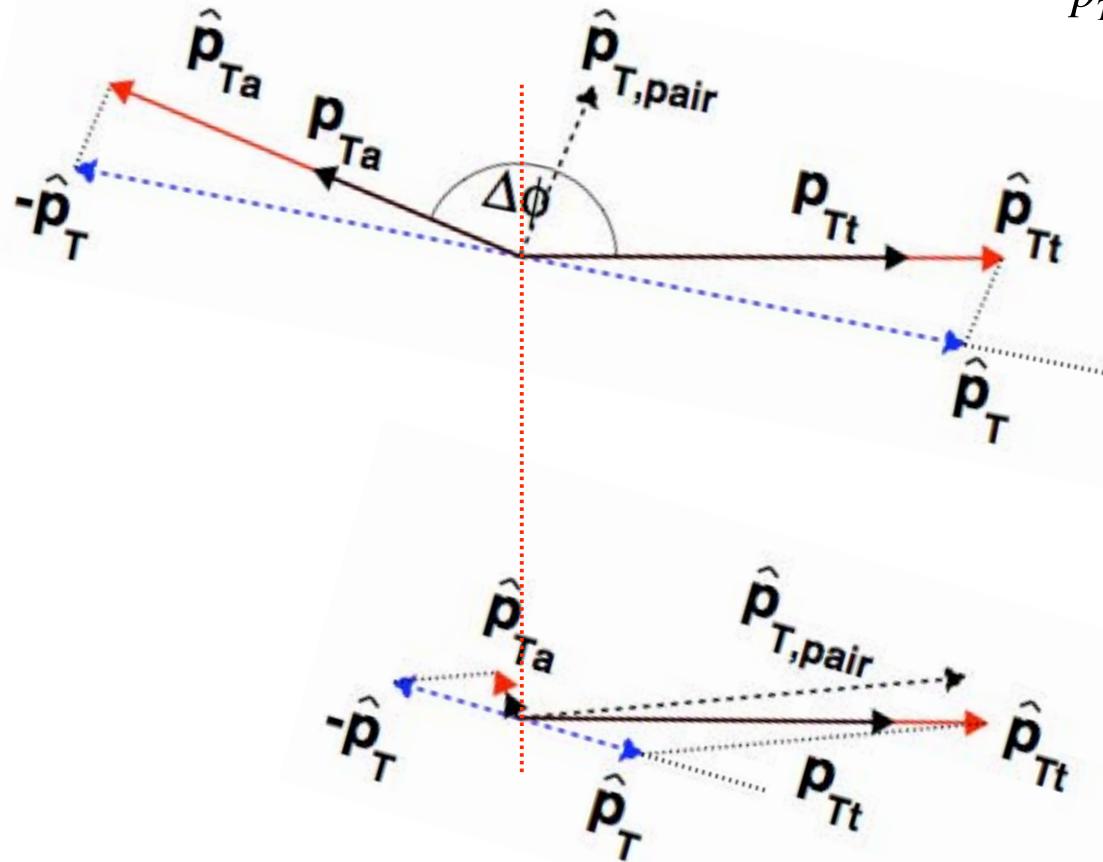
Unavoidable z-bias in di-hadron correlations

Fixed trigger particle momentum
does not fix
the jet energy!

Varying $p_{T\text{assoc}}$ with $p_{T\text{trigger}}$ kept fixed leads to variation of both trigger and associated jet energies.



k_T bias

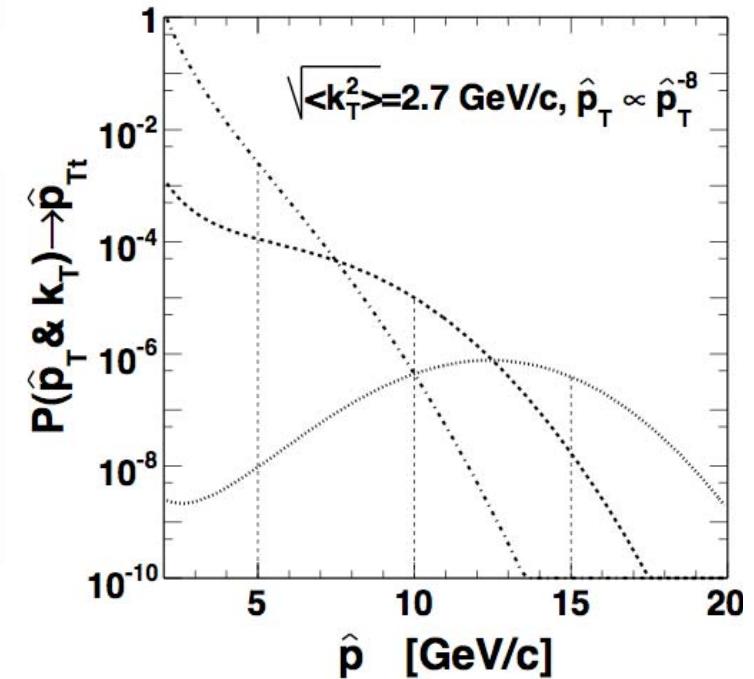


Even at relatively high photon momentum (10 GeV/c) γ -h pairs still not fully in power law pQCD regime.

$$p_{T,\gamma} \propto \text{Gauss}(\sqrt{\langle k_T^2 \rangle}) \otimes \frac{1}{\hat{p}_T^8}$$

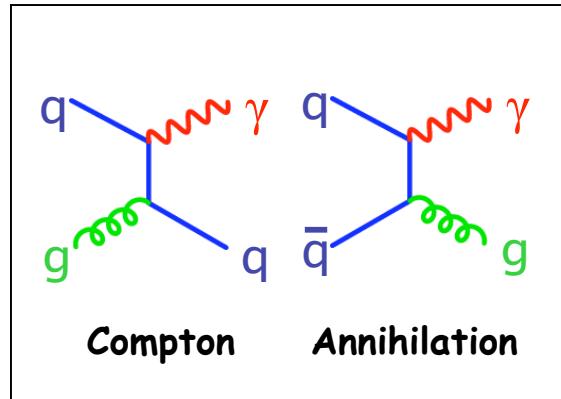
Small k_T (Gauss) and large p_T power law
less probable than

Large k_T (Gauss) and small p_T power law

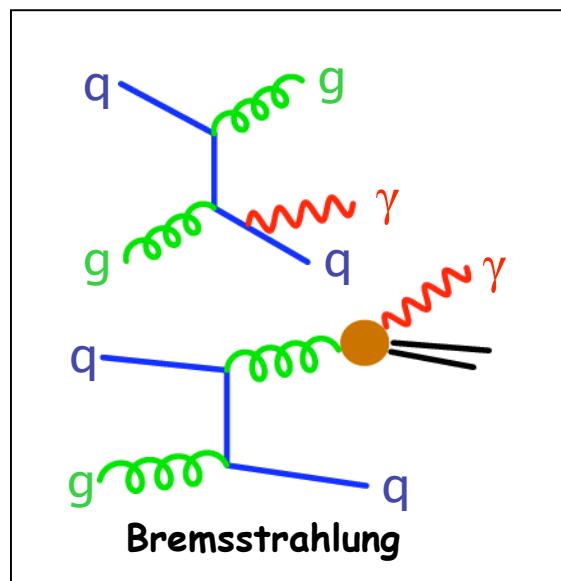


Avoidable in Direct Photons Correlations

These two diagrams fix the jet energy scale



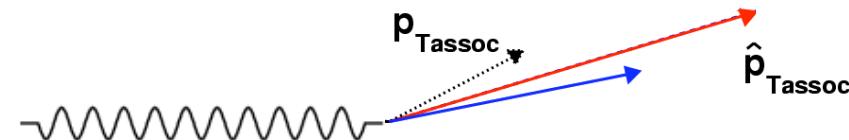
Direct Photon Processes



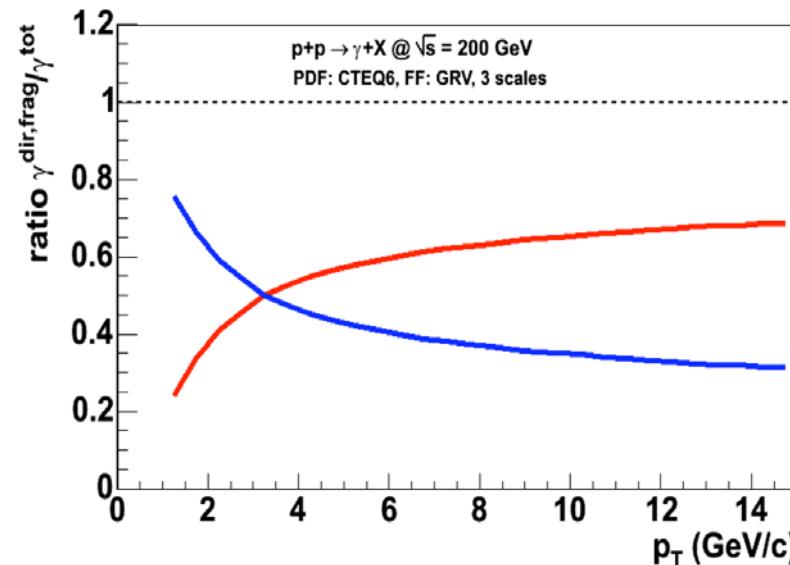
Bremsstrahlung

Up to the k_T effect !

$$z_{\text{trig}} = 1 \pm k_T / \hat{p}_T \quad \langle Q^2 \rangle \approx \text{const} \quad dN/dz_{\text{assoc}} \propto D(z)$$



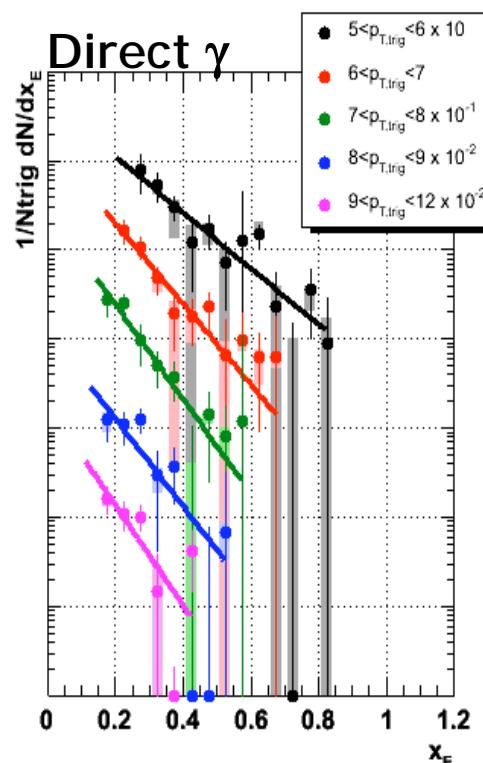
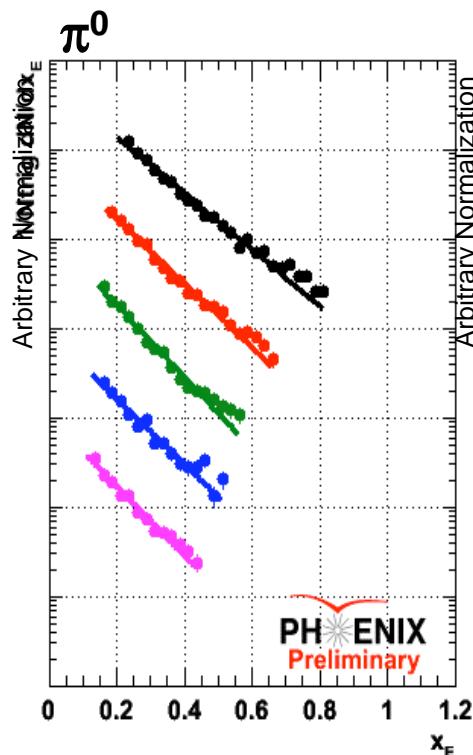
Fragmentation photons measured using isolation cut analysis



PHENIX $\sqrt{s}=200$ GeV π^0 and dir- γ assoc. distributions

Matthew Nguyen

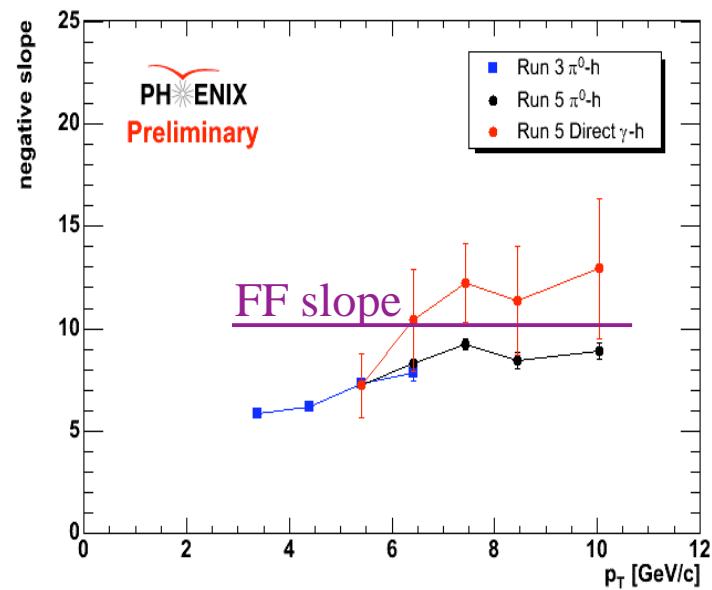
APS Spring Meeting, April 15, 2007



$$x_E = \left| \frac{\vec{p}_{Ta} \cdot \vec{p}_{Tt}}{\vec{p}_{Tt}^2} \right| = -\frac{p_{Ta}}{p_{Tt}} \cos \Delta\phi \approx -\frac{p_{Ta}}{p_{Tt}}$$

Exponential slopes still vary with trigger γ $p_{T\gamma}$.

If $dN/dx_E \propto dN/dz$ then the local slope should be $p_{T\gamma}$ independent.



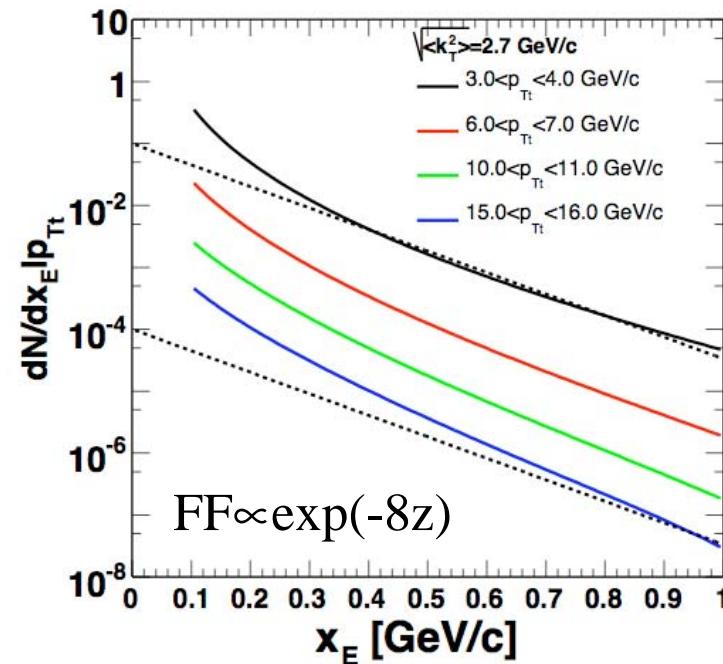
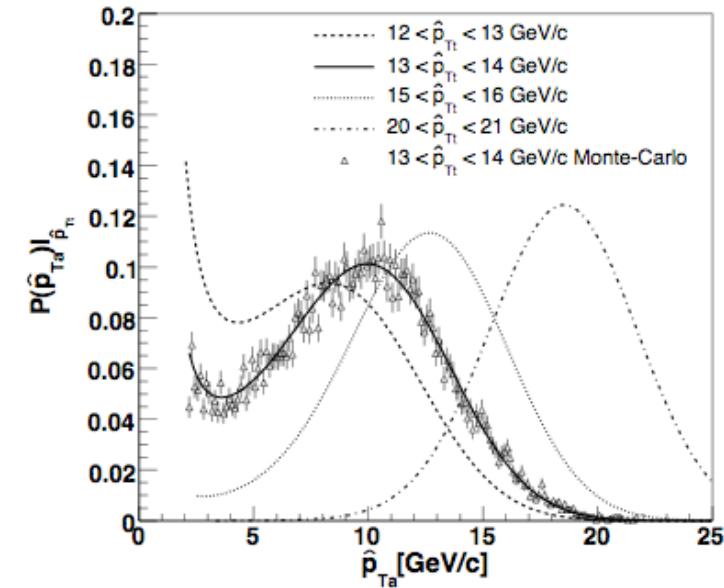
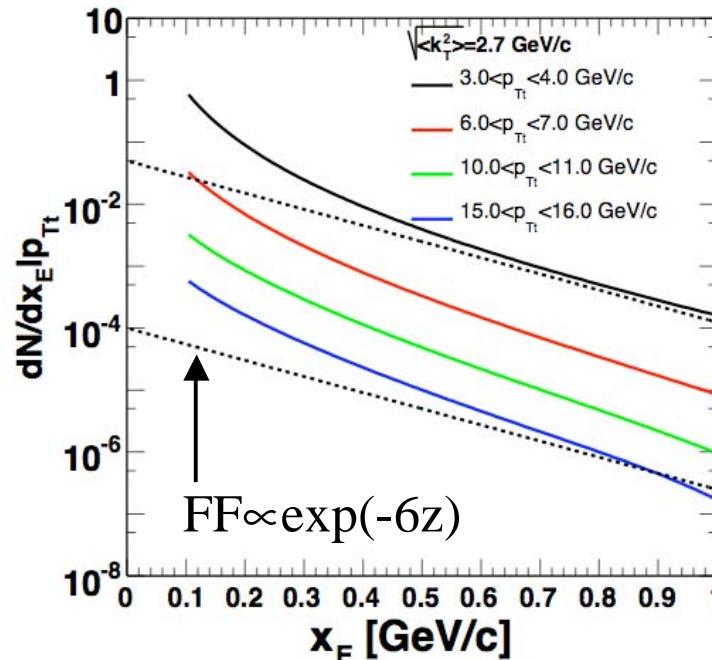
Photon associated yields - "averaged" pQCD

$$P(\hat{p}_{Tt} \& \hat{p}_{Ta}) \Big|_{\hat{p}_T} \frac{\hat{p}_{Tt} + \hat{p}_{Ta}}{\sqrt{\hat{p}_{Tt}\hat{p}_{Ta} - \hat{p}_T^2}} \exp\left(\frac{(\hat{p}_{Tt} + \hat{p}_{Ta})^2 - 4\hat{p}_T^2}{2\sqrt{\langle k_{Tx}^2 \rangle}} \right)$$

\hat{p}_{Tt} = gamma mom.

$$\frac{dN}{dp_{Ta}} \Big|_{pTt} = D(z_t) \otimes \Sigma_Q \left(\frac{p_{Tt}}{z_t} \right) \otimes \int d\hat{p}_{Tt} P(\hat{p}_{Tt} \& \hat{p}_{Ta}) \Big|_{\hat{p}_T}$$

k_T bias still important, sensitivity to the $D(z)$ shape as expected, the slope is also changing as in the data - parton imbalance.



Summary

Inclusive and two-particle correlation measurement in the high- p_T sector at RHIC opened a new window into a QGP physics. Inclusive measurements have limited discrimination power -> complementary multiparticle correlations are important. However, two-particle correlations are not bias-free either:

di-hadron correlations:

- k_T and initial/final state QCD radiation, resummation vs NLO
- j_T near-side jet shape modifications
- z-bias washes out the sensitivity of the associated x_E yield to the Fragmentation Function.

direct photon-hadron correlations

- Fragmentation function can be extracted from the associated x_E yield. However
- k_T -bias still present - pushes the minimum photon-trigger p_T above 10 GeV/c at RHIC.

Question: non-photonic e^\pm $R_{AA}^{c\text{-quark}} \approx R_{AA}^{u,d}$

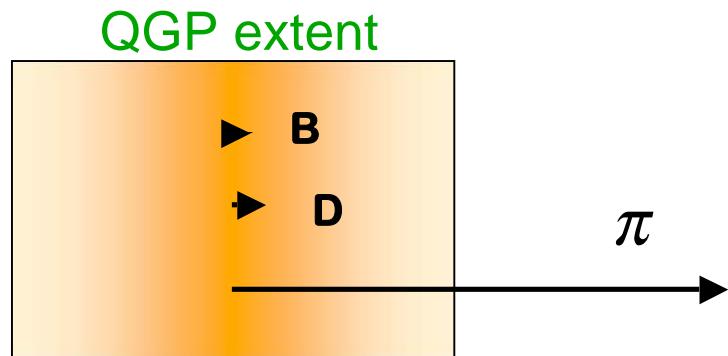
Heavy quarks are expected to loose less energy than light quarks, but @ 6 GeV/c:

charm quarks (e^\pm)
equally suppressed as
light quarks (π^0)

Radiative energy loss only fails to reproduce non-photonic e^\pm R_{AA} and/or v_2

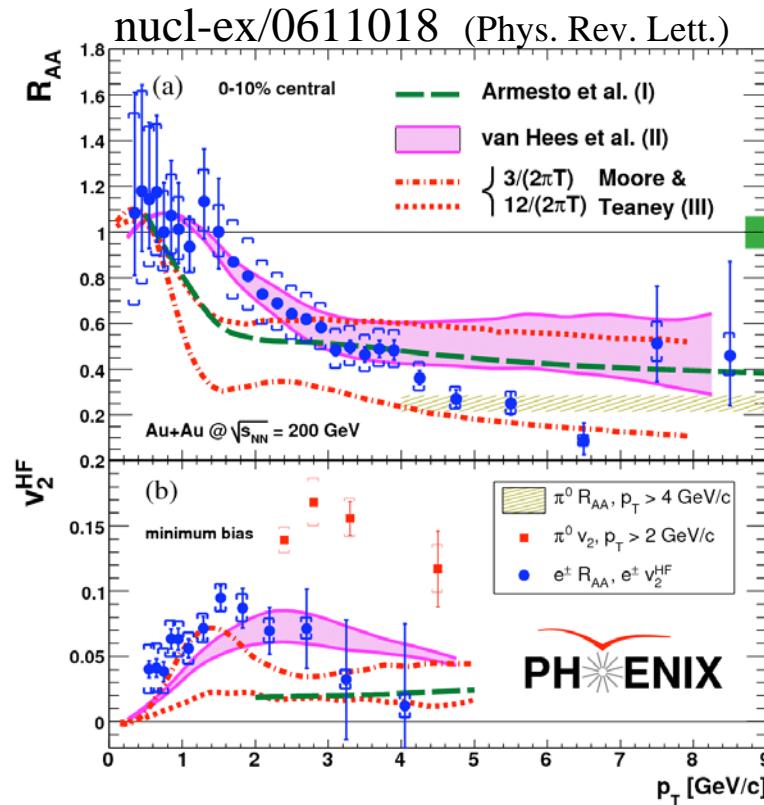
Possible interpretation:

I. Vitev (A.Adil, I.V., hep-ph/0611109)



$$\tau_{\text{form}}(p_T = 10 \text{ GeV}) = \frac{\pi}{25 \text{ fm}} + \frac{D}{1.6 \text{ fm}} + \frac{B}{0.4 \text{ fm}}$$

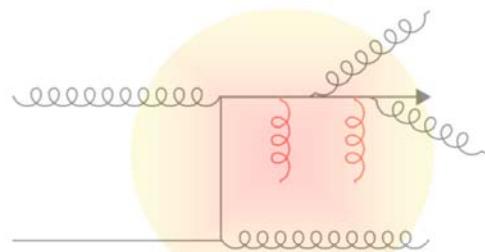
- Fragmentation and dissociation of hadrons from heavy quarks inside the QGP



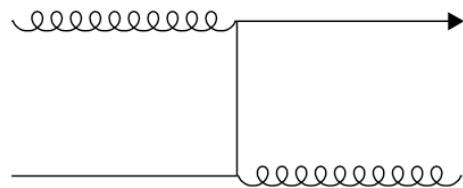
Popular interpretation - elastic energy loss

Partonic Energy Loss

Radiative $2 \rightarrow N$ processes. Final state QCD radiation as in vacuum ($p+p$ coll)
 - enhanced by QCD medium.

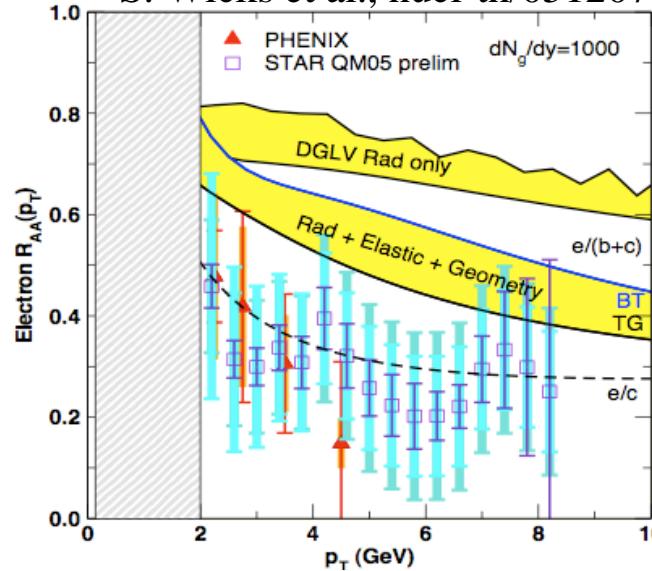


Elastic $2 \rightarrow 2$ LO processes



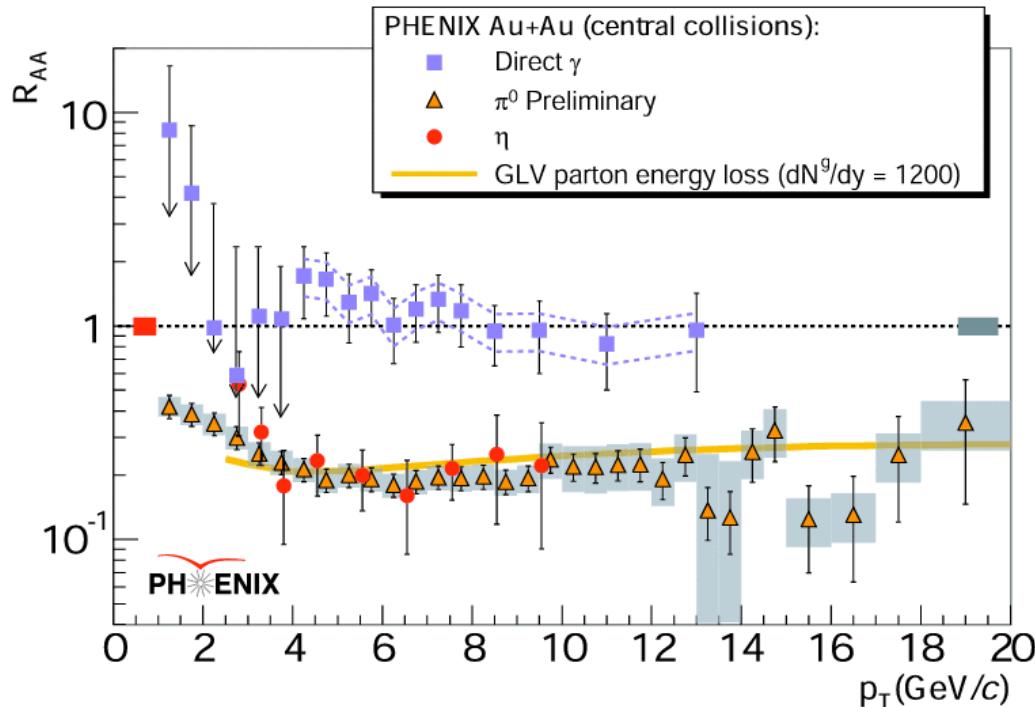
Elastic ΔE models predict significant broadening of away-side correlation peak - not seen in the data. Also various models differ significantly in radiative/elastic fraction.

S. Wicks et al., nucl-th/0512076



8 LO subprocesses

$qq' \rightarrow qq'$	$\frac{4}{9} \frac{s^2 + u^2}{t^2}$
$qq \rightarrow qq$	$\frac{4}{9} \left[\frac{s^2 + u^2}{t^2} + \frac{s^2 + t^2}{u^2} \right]$
$q\bar{q} \rightarrow q\bar{q}'$	$\frac{4}{9} \frac{t^2 + u^2}{s^2}$
.....	



$$R_{AA}(p_T) = \frac{d^2 N^{AA} / dp_T d\eta}{T_{AA} d^2 \sigma^{NN} / dp_T d\eta}$$

Measured for:

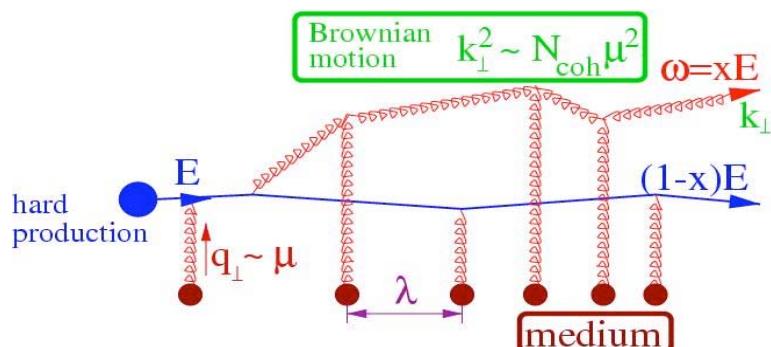
variety of species

$\pi^0, \pi^\pm, \eta, \gamma_{\text{dir}}, p, K_S, \phi, \omega, J/\psi, \Omega\dots$

and CMS energies

$\sqrt{s}=17, 22.4, 62.4, 130, 200 \text{ GeV}/c$

Jet quenching - one of the most celebrated results. Light mesons suppressed by factor of 5, direct- γ unsuppressed => FS nature of observed suppression. Data successfully described by pQCD models.



Transp. Coef. Scatt.
power of QCD med:

Density of
scattering centers

Range of
color force

$$\hat{q} = \rho \int q^2 dq^2 \frac{d\sigma}{dq^2} \equiv \rho \sigma \langle k_T^2 \rangle = \frac{\mu^2}{\lambda_f}$$

Some of the open questions

Inclusive nuclear suppression factor R_{AA} is not quite sensitive to the particular dE/dx mechanism - is it due to the *surface bias*?

Light and *heavy quarks* suppression looks similar: $R_{AA}^{c-quark} \approx R_{AA}^{u,d}$

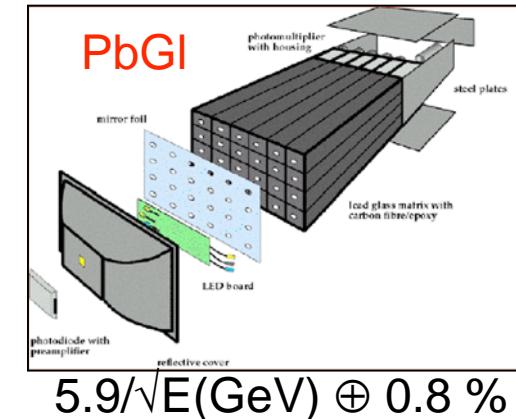
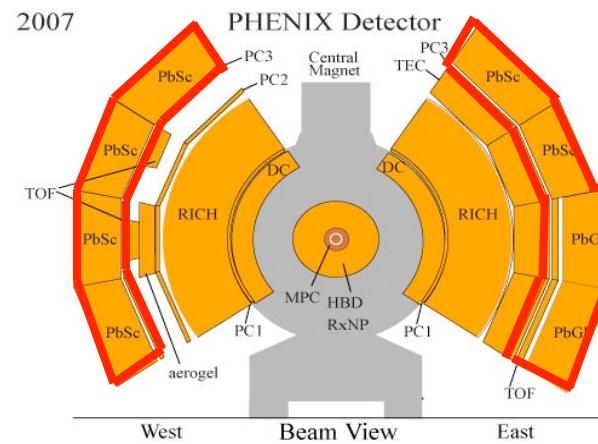
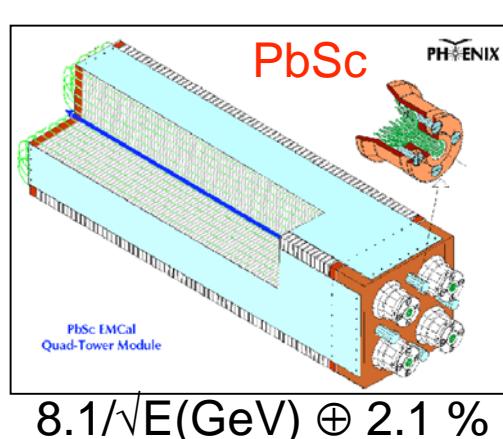
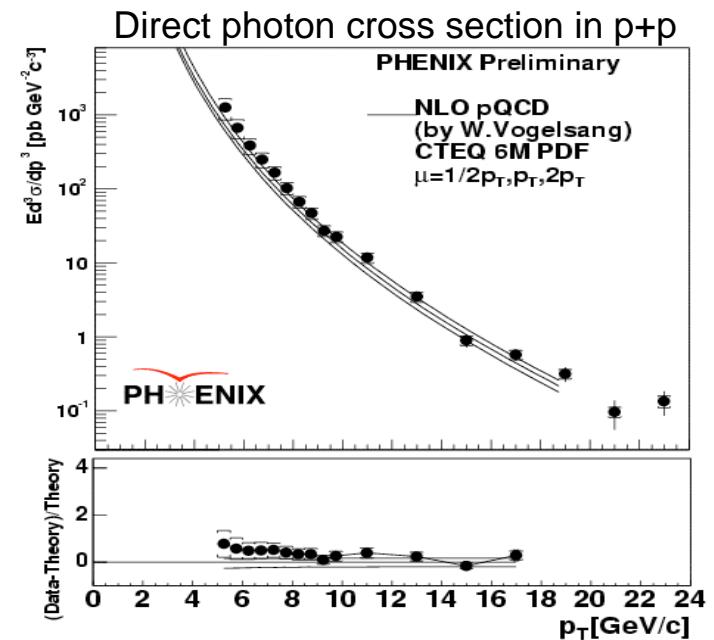
Quarks and *gluons* suppression looks similar: $R_{AA}^{quark} \approx R_{AA}^{gluon}$

Direct photon suppression at *high p_T* looks similar: $R_{AA}^{q,g} \approx R_{AA}^{gamma}$

It is evident that the detailed understanding of unmodified parton properties
CRUTIAL

Photons in PHENIX

- Two types of highly segmented EM calorimeters > 24K towers
- Photon and π^0 measurements at very high p_T
- Cross sections agree reasonably with NLO calculations



Direct γ -h Correlations in PHENIX p+p $\sqrt{s}=200$ GeV

Statistical Subtraction method:

$$\gamma_{\text{direct}} = \gamma_{\text{all}} - \gamma_{\text{decay}}$$

Matthew Nguyen

APS Spring Meeting, April 15, 2007

- Signature small near-side correlation signal apparent
- Yield sensitive to η contribution at the near-side
- Still room for some fragmentation contribution

